1.0

2.8   2.5

3.2   2.2

3.6

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Technical Report 464

TEST PROCEDURES FOR SHIPBOARD TRANSIENT PROTECTIVE DEVICES (TPD's)

J.F. Theisen
R.W. Prather

1 November 1979

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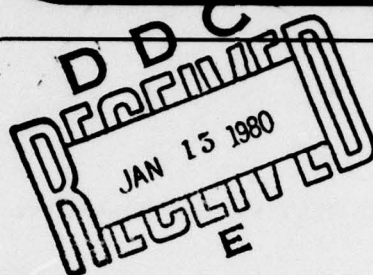
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The objective of this study was to develop the laboratory test procedures required to determine the effect of hf and vhf, shipboard-antenna transient protective devices (TPD), on the normal operational performance of hf and vhf communication systems. This is essentially a compatibility test-procedure development program.

A significant portion of the energy released during a nuclear detonation appears as an electromagnetic pulse (EMP) having spectral components at the same frequencies as those employed by many military communication and other electronic systems. Protection of these systems against this potentially destructive and/or

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disruptive effect is required to ensure mission capability during and after a critical period. The objective of this report is to document how to determine that a protective device is compatible with system requirements and that it indeed does offer protection from a typical, high-level EMP.

Requirements for transient protective devices and the text procedures and instrumentation recommended for determining the efficacy and system compatibility of selected TPD's for hf and uhf communications are listed and described.

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SUMMARY

OBJECTIVE

Develop the laboratory test procedures required to determine the effect of hf and vhf, shipboard-antenna transient protective devices (TPD), on the normal operational performance of hf and vhf communication systems. This is essentially a compatibility test-procedure development program.

A significant portion of the energy released during a nuclear detonation appears as an electromagnetic pulse (EMP) having spectral components at the same frequencies as those employed by many military communication and other electronic systems. Protection of these systems against this potentially destructive and/or disruptive effect is required to ensure mission capability during and after a critical period. The objective of this report is to document how to determine that a protective device is compatible with system requirements and that it indeed does offer protection from a typical, high-level EMP.

RESULTS

The requirements for transient protective devices (TPD's) and the test procedures and instrumentation recommended for determining the efficacy and system compatibility of selected TPD's for hf and uhf communications are listed and described.

RECOMMENDATIONS

1. Measure electrical parameters of a TPD both as a discrete component and as a part of an antenna-transmission line system.

2. Perform laboratory tests on spurious signal generation and power handling capabilities in the transmitting mode. In the receive-only mode, determine the ability of the device to protect the receiver from all possible transient pulses.

3. Shipboard testing will be limited to those tests consistent with the environmental conditions and operational requirements of a particular ship.

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1.0 INTRODUCTION

The objective of this task is to develop and document laboratory test procedures that could be used to determine the effect that high frequency (hf) and ultra-high frequency (uhf) shipboard antenna and/or transmission line transient protective devices (TPD) have on the normal operational performance of hf and uhf communication systems and indicate procedures to determine the characteristics and probable effectiveness of selected TPD's. This task is to address such things as compatibility with existing equipments and possible degradation of performance capability.

On the basis of previous experiments performed at NOSC and reported upon in two technical notes,* references 1 and 2, a listing of compatibility tests and measurements that should be made are described. Electrical parameters of importance are defined and experimental procedures are discussed.

Emphasis is placed upon the compatibility problem of the generation by a TPD of spurious frequencies—harmonics and intermodulation products in the case of multiple transmitter operation. Also of importance in the transmitter case is the ability to withstand operational levels of radio frequency power, especially upon actuation of the TPD by simulated pulses of full-threat amplitude.

Factors and possible testing techniques have been determined to be as follows:

a. System loading

b. Voltage-standing-wave ratio (VSWR)

c. Time-domain reflectometry (TDR)

d. Spurious-frequency generation of third-harmonic or inter-modulation products

e. System noise level effects

f. Firing and transient response characteristics

g. Extinguishing characteristics after TPD firings

All of the tests reported upon here will not necessarily be used in a final test sequence. The overall task is to determine all pertinent electrical parameters and, having found these, determine if the device will upset or degrade the system in which it will be installed, determine any device characteristic changes after the protective device has been installed in a circuit or system for a period of time, and establish uniform measuring techniques so that similar devices can be compared at different locations and times. In order to maintain uniformity and consistency with established EMP technology, the definitions, procedures and specifications set forth in reference 3 will, in general, be followed. These, however, will be modified or extended to satisfy Navy requirements. Performance of some of the measurements will be dependent upon the type of device and its intended application.

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*NOSC TNs are informal documents intended chiefly for internal use.

2.0 GENERAL SHIPBOARD SYSTEMS

Generally, in shipboard operation, a transmitter or receiver is not connected to an antenna directly. The confined platform that is a ship requires that receivers be protected from the ship's transmitted energy and that, when possible, antennas be shared. Multi-couplers provide both these functions by allowing simultaneous use of an antenna by several transmitting and/or receiving equipments while providing isolation between them and from extraneous signal sources. Transmitting multicouplers, because they must provide both efficient matching to the antenna and isolation between channels with low insertion loss, require a broadband antenna having a voltage-standing-wave-ratio (VSWR), on 50 ohms, of 3:1 or less. Antenna and multicoupler are normally limited to a 3:1 frequency range. Greater loss can be tolerated in receiver circuits as atmospheric noise normally determines receiver sensitivity and so limitation on permissible antenna VSWR is not as important. Greater loss is also allowed in the receiver multicoupler in order to increase off-frequency rejection. Often a single antenna suffices to cover the hf spectrum.

Antenna tuners (antenna coupler groups, single channel) provide efficient signal transfer between a transmitter or receiver and a narrowband antenna over a wide frequency range. Transmit tuners, which are usually used with 35-foot whips, cover the hf spectrum of 2 to 30 MHz and are capable of matching a wide range of antenna impedances to a 50 ohm transmission line. However, off-frequency rejection of tuners is poor, and, for duplex operation, additional receiver protection is provided. Receiver antenna-coupler groups are usually operated with short whips and are tunable over a narrower frequency range.

The rf path from transmitter/receiver to antenna is normally through patch panels and/or a switch matrix for greater operating flexibility. When different mixes of transmitters, couplers, receivers, etc., make up the total communication system, their control and rf functions must be compatible. If they are not, interface equipments are required.

Performance of many of the broadband antennas, especially for 2-6 MHz, is dependent on the surrounding mast or superstructure and in fact, the superstructure is part of the antenna. Because the surrounding structure influences the antenna pattern and impedance, and structures differ for different ships of the same class, each 2-6 MHz broadband antenna is custom designed for a particular ship. Broadband antennas, however, such as the discage or grounded discone, have similar electrical characteristics (not necessarily pattern) with proper mounting location.

Upon these complex systems may be incident the electromagnetic-pulse (EMP) engendered by an exoatmospheric nuclear burst purposely made to produce abundant gamma rays. These gammas produce Compton electrons in the atmosphere which being accelerated produce the EMP—a 10-nanosecond risetime pulse with an electric field amplitude possibly as great as 50 kilovolts/metre. That system protection against 5×10^{12} (volt/metre)/second would be "desirable" is rather self-evident. The EMP will be discussed shortly in more detail. It is some proposed shipboard EMP protective devices, their operating characteristics, and their effect on compatibility that is the subject of this report.

Even under present normal conditions, shipboard topside harmonic and inter-modulation levels from non-linear devices and objects greatly affect receivability and/or compatibility. As protective devices could introduce nonlinear elements at critical points (for example, in a multi-frequency transmitting antenna) the very real intermodulation

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problem may be exacerbated. An early discussion of shipboard intermodulation is contained in reference 4. Following are the results reported by Chase, et al., as of 1965.

> *"Intermodulation aboard ship is a major cause of interference to receiving systems and is greatly aggravated by the use of many simultaneous transmissions. When seven or more transmitters are used simultaneously, the probability of interference on any receiving frequency is very great. For example, ten transmitters can produce 100,000 products up through the 7th order.*
>
> *The most serious cause of intermodulation is in the receivers if they are unprotected by narrow bandpass filters. Use of good two-section filters will practically eliminate the receivers as significant sources of intermodulation.*
>
> *With protected receivers the most serious cause is the topside environment (including antenna systems). Topside environmental effects typically result in 3rd-order products about 60 dB above receiving system threshold with 5th-order products about 40 dB above it.*
>
> *The transmitters are not major causes of the intermodulation considered here. Although single-section multicouplers do not isolate the transmitters sufficiently, two-section multicouplers are ample for most situations."*

More recent information on the problem of intermodulation production is covered in references 5, 6, and 7.

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3.0 THE EMP ENVIRONMENT

The electromagnetic pulse environment involves subjecting a ship's communication and electronic systems (mainly antennas and transmission lines) to an electric field possibly as great as 50 kilovolts/metre. This 10-nanosecond risetime field could well be polarized in the same direction as an antenna or conductor resulting in a requirement for protective devices for existing systems and design requirements for future transmitter/receiver systems.

The low-altitude EMP is produced by the products of a surface or near surface nuclear explosion that interacts with air molecules to produce a separation of electrical charge, thus creating a momentary electric dipole. Very high energy gamma rays and x-rays are produced and propagate radially away from the burst. These gamma and x-rays collide with atmospheric atoms to produce Compton electrons which continue in the radial direction at relativistic speeds. The "heavy" positive ions are left behind resulting in a large separation of opposite charges. This is the mechanism that initiates the electromagnetic pulse. These Compton electrons lose energy in collisions with neutral air molecules, producing secondary electrons. The atmosphere becomes conducting and highly ionized and the separated charge begins to discharge with current flow, creating a current-dipole-moment. At large distances the $1/r$ field from this charge separation and relaxation appears as emanating from a very-fast transient electric dipole.

In high-altitude, exoatmospheric detonations, the charge separation occurs mainly in or below the region of the upper atmosphere containing the ionospheric D-layer. In this region the Compton electrons travel a sufficient distance that the earth's magnetic field produces a curvature of their path sufficient to produce a resultant magnetic dipole moment. The source region where charge separation occurs covers a very large area and the resulting EMP is a quite-strong, plane wave with about the same intensity over a region extending from horizon to horizon or many hundreds of miles.

The characteristics of a high-altitude EMP waveform are quite variable and depend upon weapon characteristics and the relative position of a ship or observer. All metallic parts of a ship are in effect "antennas" and the ocean is a good reflector so that coupling analysis is indeed very complex. An approximation for the field-strength E(t) of an incident pulse is a double-exponential wave-form given by:

$$E(t) = E_0[\exp(-\alpha t) - \exp(-\beta t)]$$

$$= E_0[\exp(-t/\tau_1) - \exp(-t/\tau_2)] \text{ volt/metre}$$

where $\tau_1 = 1/\alpha$ is the pulse-decay time constant and $\tau_2 = 1/\beta$ is the pulse-rise-time constant. Various values are used in the literature; τ_1 varying from 2.5 to 6.7×10^{-7} seconds and τ_2 from 2.1 to 3.8×10^{-9} seconds. As $\tau_1 \gg \tau_2$, E_0 is approximately the peak value of the incident pulse, and 5 to 5.3×10^4 volts/metre. In magnetic terms we would then have:

$$H(t) = E(t)/\eta_0 \text{ ampere/metre}$$

or

$$B(t) = E(t)/c_0 \text{ Tesla (Weber/metre}^2),$$

where $\eta_o = 120\pi$ ohm/square and $c_o = 3 \times 10^8$ metre/second.

Figure 1 is a plot of the first 150 nanoseconds for the indicated double-exponential pulse with a 10-nanosecond risetime to 47.7 kV/m, an E_o of 50 kV/m. It is interesting to note that this waveform could, to a first approximation, appear as a triangular pulse, being a scalene triangle with an initial slope of about 1.4×10^4 (V/m)/nanosecond and a final slope of about -1.5×10^2 (V/m)/nanosecond.

The Fourier transform of the double-exponential is

$$E(\omega) = E_o \frac{\tau_1 - \tau_2}{(1 + i\omega\tau_1)(1 + i\omega\tau_2)} \text{ volt second/metre.}$$

This becomes $E_o(\tau_1 - \tau_2)/[(1 - \omega^2\tau_1\tau_2) + i\omega(\tau_1 + \tau_2)]$, and as $\tau_1 \gg \tau_2$, it is approximated by $E_o\tau_1/[(1 - \omega^2\tau_1\tau_2) + i\omega\tau_1]$. As $\tau_1\tau_2 = 2.5 \times 10^{-15}$, at low frequencies where ω^2 is relatively small, we can approximate with $E_o\tau_1/(1 + i\omega\tau_1)$ or $E_o\tau_1(1 - i\omega\tau_1)/(1 + \omega^2\tau_1^2)$. Thus at low frequencies the transform is essentially a constant at $E(\omega) \cong E_o\tau_1$.
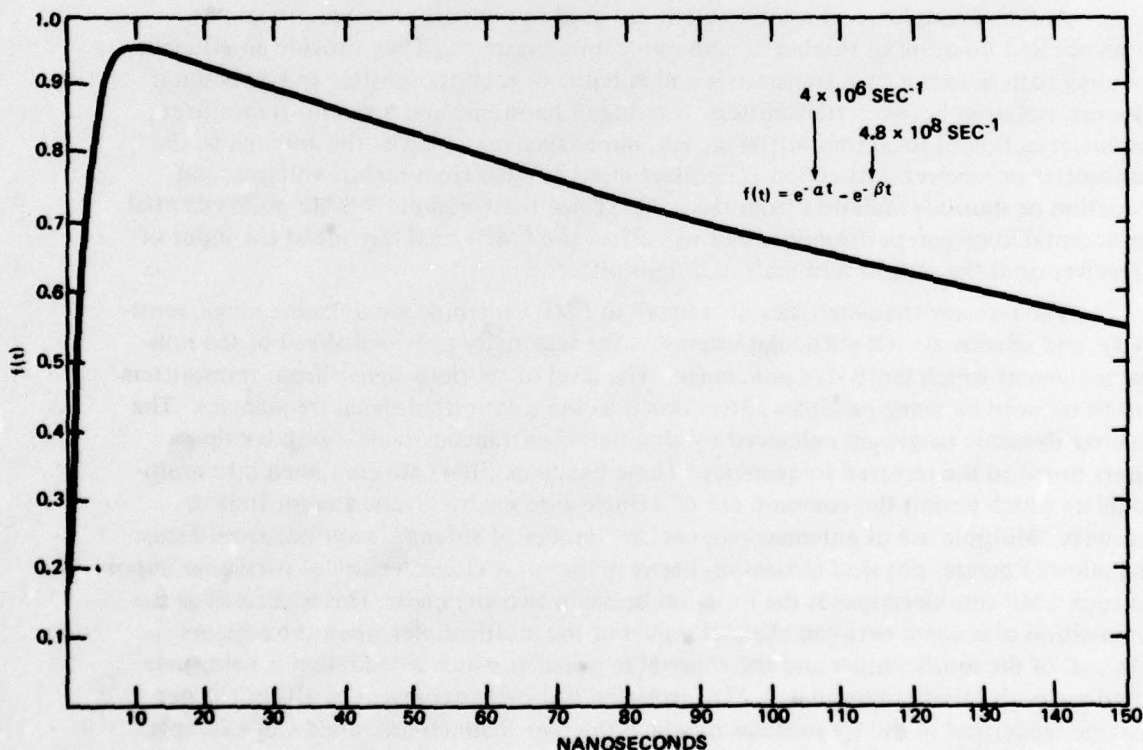

Figure 1. Early-time history of a typical theoretical electromagnetic pulse approximating a scalene triangle.

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Spectral components range from almost direct-current to the order of 100 MHz as shown in Figure 2 (compiled from reference 8). Figure 3 is compiled from reference 3 in order to illustrate the magnitude of the EMP problem at the base or terminal of antennas. A TPD would normally be incorporated into a loaded system, but there could be times when it would be subjected to the open-circuit condition.

The Defense Nuclear Agency has published several "handbooks" on EMP, and one in particular, although very broad in considerations and oriented mainly to land-based systems, is very useful as a reference. This is DNA 3286H, our reference 3. In Appendix A are excerpts from DNA 3286H which are representative EMP induced transients calculated for 3 and 30 metre "monopoles" over a good-conducting ground plane illuminated by the EMP of Figure A-1. These are reproduced to illustrate the magnitude of the hardening problem. As one would expect, antennas tend to "ring" at their resonant frequency.

The rather large EMP signals appearing at antenna terminals will, in general, appear at system terminals by way of tuned filter circuits called multicouplers. The system-terminal EMP then will be a modification of that induced in the associated antenna. Ship-board radio communications systems have certain restraints or requirements imposed on them because of their operational and physical environments. Principally, these include the limited space available for antennas and the simultaneous transmission on a number of channels at relatively high power levels with limited frequency separation. These conditions can result in interference because of coupling between antennas, spurious emissions from transmitters, and limited dynamic ranges of the receivers.

Antenna couplers and multicouplers are used to improve the operational performance and function of shipboard communications systems. They provide an efficient coupling path between each transmitter and antenna or each transmitter and a common antenna, isolation between transmitters, filtering of harmonic and spurious transmitter output, rejection of local transmitter signals, impedance matching of the antenna to the transmitter or receiver, protection of receiver input circuits from high rf voltages, and reduction or spurious radiation from receivers. Thus, these equipments are quite essential for acceptable system performance and will affect the EMP signal arriving at the input of a receiver or at the output terminals of a transmitter.

The receiver characteristics of concern in EMP hardening are dynamic range, sensitivity, and selectivity. Of particular interest is the selectivity provided ahead of the non-linear element which limits dynamic range. The level of spurious signals from transmitters can be reduced by using bandpass filters tuned to the transmitted signal frequencies. The receiver dynamic ranges are enhanced by eliminating extraneous signals with bandpass filters tuned to the received frequencies. These bandpass filters are combined into multicouplers which permit the common use of a single antenna by several transmitters or receivers. Multiple use of antennas reduces the number of antennas required aboard ship and allows a greater physical separation between them. A characteristic of particular importance in EMP considerations is the isolation between two channels. This is defined as the attenuation of a signal between channel inputs of the multicoupler when the antenna terminal of the multicoupler and the channel terminal at which attenuation is being measured are both suitably terminated. The isolation is usually expressed in dB for the percentage separation of the frequencies to which the two channels are tuned (for example, 40 dB at 5 percent). Details of these coupling devices and their selectivity characteristics are documented in reference 9.
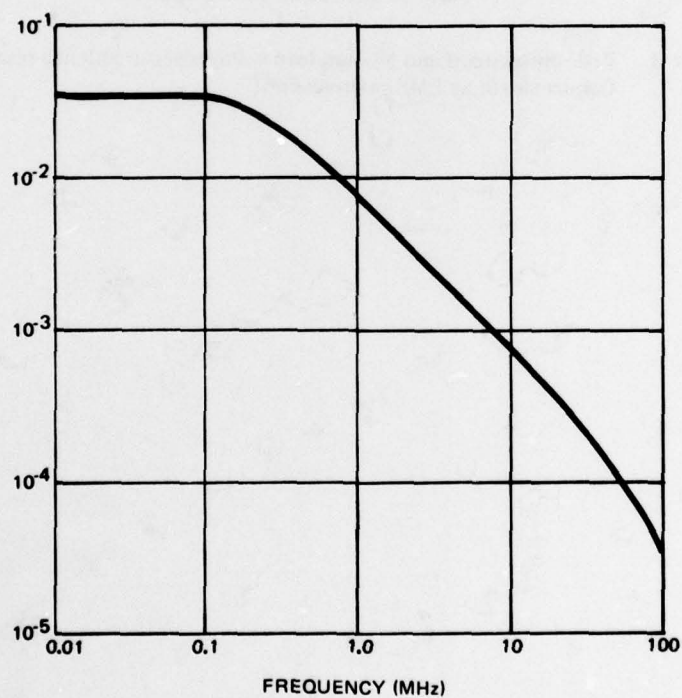
Figure 2. The double-exponential waveform in kilovolt/metre and its Fourier transform or "spectrum" in volt-second/metre. Pulse constants are: $E_0 = 5 \times 10^4/0.9646$ volt/metre, $\tau_1 = 6.7 \times 10^{-7}$ second, and $\tau_2 = 3.8 \times 10^{-9}$ second.
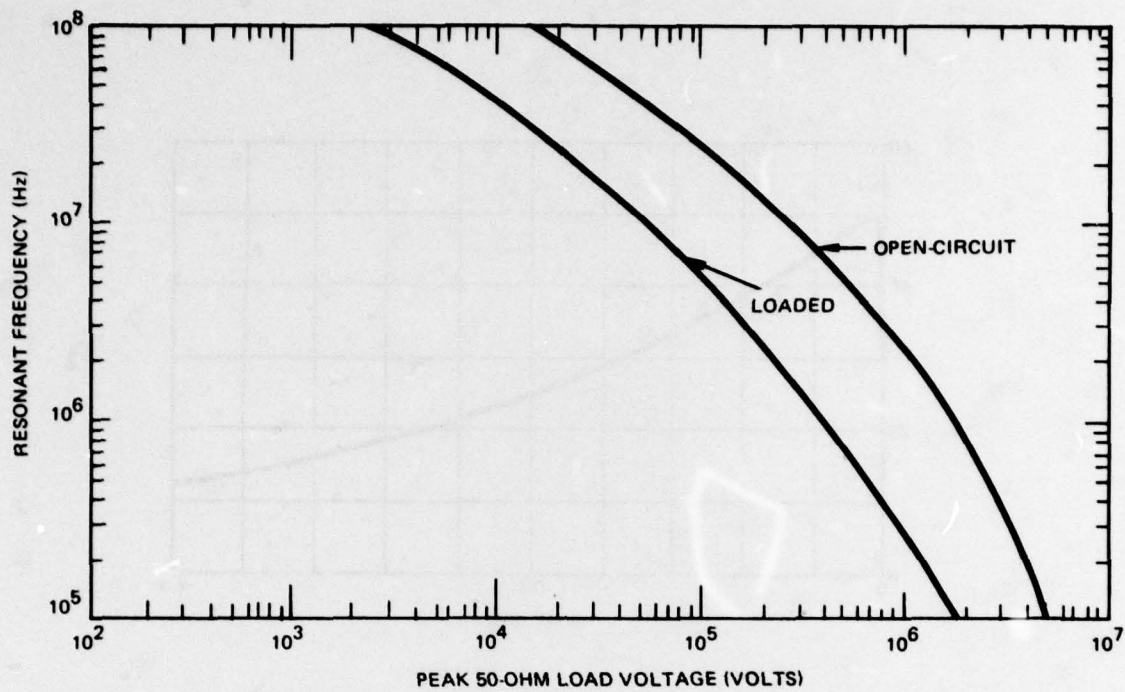
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Figure 3. Peak open-circuit and 50-ohm-load voltages versus antenna resonant frequencies in an EMP environment.

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4.0 TRANSIENT PROTECTIVE DEVICE TESTS

After it has been determined that a protective device is required or recommended for installation in a particular circuit or system and after an "off the shelf" or specially designed device has been procured, a series of tests and measurements are required before permanent installation in a system can be made. The devices referred to in this report are considered only as "black boxes." No assumptions are made as to what type of electrical components are involved nor are any electrical parameters specifically assumed.

This report considers two facets as applied to Navy communications systems and recommends the measurements to be made, why these measurements are of importance in systems in general, and typical instrumentation and techniques to make these measurements.

First, it is necessary to consider passive compatibility of a surge protective device with a system when the device is installed but not triggered. Second, if a device is installed in a system, the transient response of the device and system when the device is triggered must be considered and, if possible, measured.

4.1 COMPATIBILITY

Compatibility requirements necessitate the following:

(a) Determine electrical parameters.

(b) Determine if device will upset or degrade the system in which it might be installed.

(c) Determine any device characteristic changes after the protective device has been installed in a circuit or system for a period of time.

(d) Establish uniform measuring techniques so that similar devices can be compared at different locations and/or different times.

(e) In order to maintain uniform consistency with established EMP technology, follow the definitions, procedures and specifications set forth in reference 3, modified or extended to satisfy Navy requirements.

(f) Depending upon the results of initial measurements and on system specifications and requirements, recommend which measurements are to be made part of a standard test procedure.

A preliminary look at a protective device schematic diagram and type of components will give some general indication of device electrical parameters and indicate the probability of nonlinear characteristics (e.g., use of diodes, dissimilar-metal junctions, etc.). It might thus be possible to quickly determine the acceptability of a particular device in the system under consideration. Performance of some of the measurements will be dependent on the type of device and/or its intended application, such as topside or below-deck, etc.

Initial measurements should then be made to determine electrical parameters of the protective device, both external to and, if possible, when included in a transmission-line system. These include but are not necessarily limited to the first four of the following. The remaining five require rather elaborate laboratory procedures:

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(1) Shunt resistance (R_S)

(2) Shunt capacitance (C_S)

(3) Series inductance

(4) Impedance (Z) and phase angle (ϕ)

(5) Insertion loss and VSWR

(6) Intermodulation products and harmonic generation

(7) Receiver noise level effects

(8) Power handling capability

(9) Time domain reflectometry

4.1.1 Shunt Resistance (R_S)

The shunt resistance, R_S, of a protector is the dc insulation resistance at a particular test voltage. Changes in shunt resistance can be and sometimes are used as a failure criterion for permanent degradation indications.

R_S can be measured using equipment such as a General Radio type 1864 megohm-meter or an AN/PSM-2 constant voltage megger. The latter instrument is used for shipboard cable continuity and insulation measurements. Test voltages should be up to a value near but less than the static breakdown voltage, V_{SB}, of the device. The G-R type 1864 megohmmeter provides test voltages from 10 to 1090 volts dc.

4.1.2 Shunt Capacitance (C_S)

The shunt capacitance, C_S, of a protective device is mainly the electrode to electrode capacitance of a gaseous discharge device. Shunt capacitance can have a significant effect on both the transient and steady-state response and may limit possible applications of a protective device even though it may not have been an important factor in the initial design application. In a radio frequency circuit, consideration must be given to C_S and its effect on circuit impedance at all operating frequencies.

C_S can be measured with an instrument such as the General Radio type 1650 impedance bridge, the Hewlett-Packard 4332A LCR meter, or a Tektronix type 130 L-C meter.

Some devices, such as spark gaps, have a rather small shunt capacitance, therefore only an order of magnitude can be specified or accurately measured. Also, shunt capacitance of some devices depends on dc bias voltage and this should be considered. The General Radio 1650B Impedance Bridge can measure capacitance with as much as 600 volts of bias.

4.1.3 Series Inductance (L_S)

Inductance of a device as well as additional inductance added to the circuit in which a TPD is installed should be considered, especially in terms of its effect on any tuning network in the system. In high frequency systems this effect might be compensated

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for by adjusting tuning controls or components. At ultra high frequencies, additional inductance might have an unalterable effect.

Series inductance can be measured with an instrument such as a Hewlett-Packard type 4332A LCR meter or a Tektronix type 130 L-C meter. Measurement system lead inductance must be taken into account in this measurement and compensation applied, if possible.

4.1.4 Impedance (Z) and Phase Angle (ϕ)

Shunt resistance (R_S) and shunt capacitance (C_S) will likely give some indication of the expected performance of a protective device in any circuit. However, to determine characteristics of a device at particular radio frequencies, as required, it is necessary to measure the impedance characteristics of the circuit or system before and after the device is installed. Measurements can be made by installing the device in a measurement setup using a vector impedance meter such as Hewlett-Packard type 4815A or a bridge arrangement, with rf oscillator and detector.

Measurements should be made at all important operating frequencies or at increments close enough to be able to ascertain values at any operating frequency.

Measurement capabilities also may be available to provide continuous frequency coverage capability over a selected range of frequencies using sweep frequency techniques.

A protective device would probably be represented as a "lumped" constant—L, C or R installed at a particular point in a circuit or system. Figure 4 is the schematic of one uhf measurement system for a large frequency range. A similar system can be devised for hf.
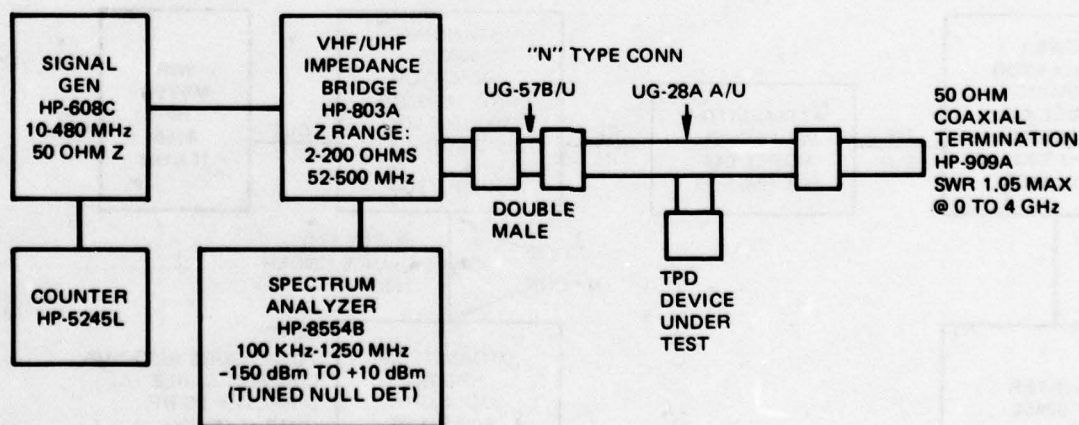
Figure 4. Impedance measuring system for uhf TPD's.

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4.1.5 Insertion Loss and VSWR

Insertion loss due to the installation of an additional component (such as a surge protective device) in a circuit might be predicted from basic electrical parameter measurements. However, a convenient and readily interpretable system utilizing sweep frequency techniques, such as the Hewlett-Packard 8620 family of solid-state oscillators, will conveniently indicate insertion loss as a function of frequency over any required frequency range. Figure 5 shows an alternate system which might be used for uhf insertion-loss measurement, and Figure 6 is a system for VSWR measurement.

Figure 5. Insertion-loss measuring system for uhf TPD's.

Figure 6. VSWR measuring system for uhf TPD's.

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In a system operating with applied rf power, the significance of power being dissipated in the protective device must be considered. Insertion loss in this system can be measured by installing an rf power meter at the appropriate locations and measuring the power on each side of the protective device.

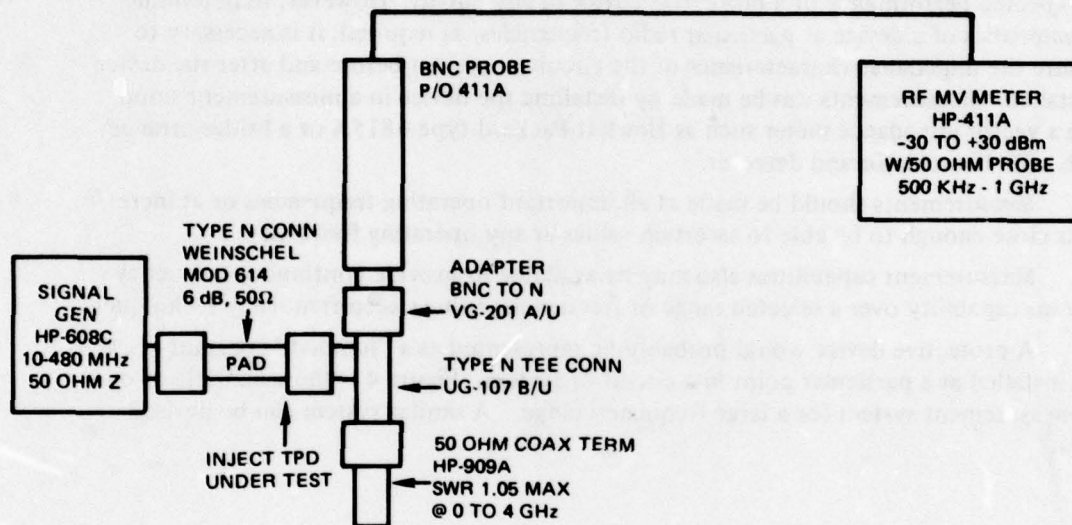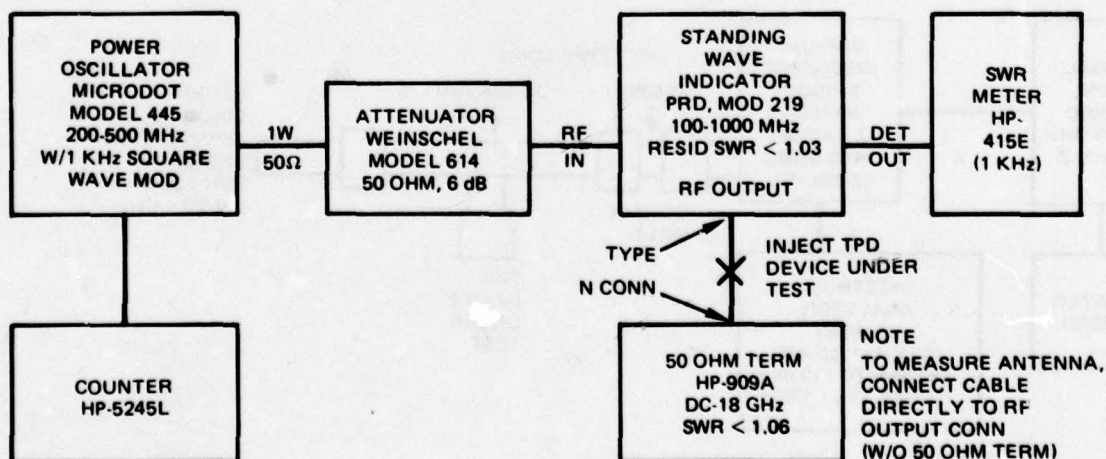### 4.1.6 Intermodulation Products and Harmonic Signal Generation

The Navy is and has been keenly concerned with spurious emissions of electromagnetic interference caused by nonlinear elements that exist in shipboard equipments or structures. These spurious emissions, or intermodulation products present EMI and EMC problems which seriously affect the operational capability of many ships in the fleet. An extensive ongoing program is especially concerned with elimination and control of hull generated interference sources caused by various mechanical bonding and grounding techniques. Similarly, the installation of any nonlinear electronic component in shipboard equipment has the potential of causing additional EMI and EMC problems.

Nonlinear characteristics of a protective device that might be installed in a circuit or system must be determined to ensure that the device does not generate unwanted signals within the frequency range of any other system. The special case of shipboard installations involves situations where many transmitters, receivers and antennas are close to each other and operating over the whole spectrum of radio frequencies from very low frequencies (kilohertz), high frequencies (2 to 30 MHz) and very high frequencies (30 to 76 MHz), to ultra high frequencies (225 to 400 MHz).

If an rf signal of frequency f_1 is applied to an electrically nonlinear element, the output frequency spectrum of this nonlinear element will contain not only the fundamental frequency, f_1, but also frequencies harmonically related to f_1, frequencies $2f_1$, $3f_1$, $4f_1$, etc. If two fundamental signals at nonharmonically related frequencies f_1 and f_2 are applied to the nonlinear element, the output from the nonlinear element will contain not only harmonic frequencies $2f_1$, $3f_1$, $4f_1$, etc., and $2f_2$, $3f_2$, $4f_2$, etc., but also frequencies which are related to the fundamentals as follows:

$$f_1 \pm f_2 \qquad\qquad 3f_1 \pm f_2$$
$$2f_1 \pm f_2 \qquad\qquad f_1 \pm 3f_2$$
$$f_1 \pm 2f_2 \qquad\qquad 3f_1 \pm 2f_2$$
$$2f_1 \pm 2f_2 \qquad\qquad 2f_1 \pm 3f_2 \qquad \text{etc.}$$

These frequencies are called intermodulation products.

It can be seen that the addition of more sources will result in intermodulation products throughout the spectrum of any system. It is necessary to measure as many intermodulation products as needed to determine the effect of these additional discrete frequencies on the particular system under consideration. For example, a nonlinear element in a high frequency system might affect a system operating at a different part of the frequency spectrum.

Considerations must be given to coupling between antennas of different systems, especially to systems where transmitters and receivers might be operating simultaneously on a common antenna by means of multicouplers. This is the condition that prevails

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aboard ship and makes measurements of these spurious signals difficult. This difficulty exists because most transmitters do generate rather considerable third harmonics and therefore, a very good low-pass filter for purity of the signal is essential in the system before meaningful measurements can be made either in the laboratory or aboard ship. The requirement of low-pass filters at each transmitter limits the frequencies that can be used. A single frequency from each transmitter will suffice for TPD testing as any non-linearity should be rather independent of frequency.

Multicoupler groups can be used to combine two transmitter signals into an antenna with a TPD installed or into a TPD with a dummy load (must be a linear one). Another port is tuned to the expected, extraneous signal for analysis by a spectrum analyzer or receiver. This procedure is complicated by nonlinearities inherent in the couplers themselves. Aboard ship, it is predicted from past experience at NOSC, that the nonlinearities in the topside environment will preclude meaningful measurements. Reference 10 documents the environmental problem. Figure 7 shows such a system for uhf measurements in the laboratory at NOSC.

Experiments have shown that a new or "cleaned-up"—that is, no poor connections— hf coupler group will produce, at best, –60 dBm of third order intermodulation products from two 1-kilowatt transmitters. Experience has shown that, in general, a system that produces either no or a minimal third harmonic from a single transmitter will produce no or minimal intermodulation products from two or more transmitters. This fact may be used to simplify the testing of TPD's for compatibility with respect to extraneous signal generation.

Laboratory experiments at hf have been made at NOSC and reported in reference 1 on several orders of harmonic generation in TPD's. This was at a 1-kilowatt power level from an AN/URT-23 transmitter operating through an elaborate filter system into a linear load. The load consisted of 3093 feet of RG-214 coaxial cable (4 dB/100 feet) terminated in a 50 ohm, deposited-film, 500-watt resistor.
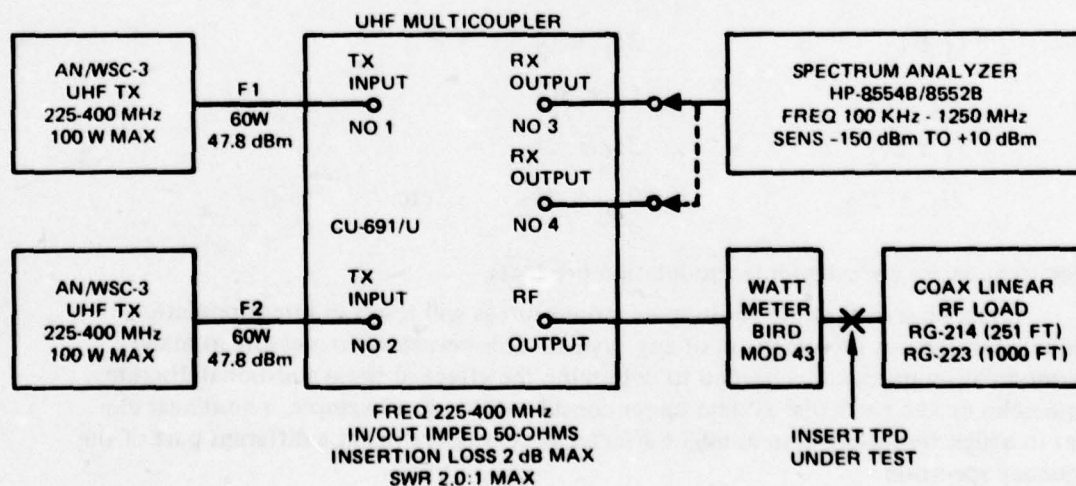

Figure 7. Intermodulation-product measuring system for uhf TPD's.

Two URT-23 transmitters would allow intermodulation product generation measurement in TPD's by combining signals in an AN/SRA 56, 57, or 58 coupler group. This is true providing the coupler does not itself generate intermodulation. The same could be done at a higher power level of 3 kilowatts by using SRC-16 transmitters and coupler group OA-4625/SRC-16 or OA-4624.

Similar experiments at uhf are much easier in that the equipment is much less massive and somewhat more easily obtainable (see Figure 7). It consists of two AN/WSC-3, uhf transmitters which are to be combined with a CU-691/U antenna coupler. The CU-691/U is manually tunable and permits four separate transmitter and/or receiver combinations to operate simultaneously into a common antenna or load; it consists of eight silverplated cavities, each a ¼-wavelength, shorted, coaxial element which is aperture coupled in groups of two to form four dual-cavity filters.

Two in-band frequencies, for example, $f_1 = 345$ MHz and $f_2 = 370$ MHz are chosen. Table 1 lists some of the possible intermodulation product frequencies to ninth order, with those that would fall within the communication band of interest marked with an asterisk. The 60-watt power at f_1 and at f_2 is dissipated in a long and linear transmission line; as an example, 4 dB/100 feet for 251 feet of RG-214 and 8 dB/100 feet for 1000 feet of RG-223; for a total of 90 dB of one-way transmission.

Table 1. Intermodulation product (IM) frequencies.

$$f_1 = 345 \text{ MHz}, f_2 = 370 \text{ MHz}$$

$$2f_1 - f_2 = 320*$$

order 3

$$2f_2 - f_1 = 395*$$

$$3f_2 - 2f_2 = 295*$$

order 5

$$3f_2 - 2f_1 = 420$$

$$4f_1 - 3f_2 = 270*$$

order 7

$$4f_2 - 3f_1 = 445$$

$$5f_1 - 4f_2 = 245*$$

order 9

$$5f_2 - 4f_1 = 470$$

The TPD is to be placed in series with a Bird wattmeter at the output-to-load port. A sensitive receiver or a Hewlett-Packard 8554B/8552B spectrum analyzer at the receiver output port of the coupler is to be used either in the search for or in the measurement of harmonics and intermods. It then remains to determine if the levels of any spurious signals detected are compatible with the constraints of a particular system. Experience has shown that a simple "bad" connection can generate an intermod level of -10 dBm at a TPD. This is attained at a 47.8 dBm (60 watt) driving level.

4.1.7 Receiver Noise Figure

Receiver noise figure measurements with and without a protective device installed should be made to determine possible receiver degradation when a protective device is installed in the system. A typical hf noise figure measurement system is shown in Figure 8. At the same time the sensitivity of the receiver system can be measured over the required frequency range. It will probably be found that the devices have no effect on the noise figure.
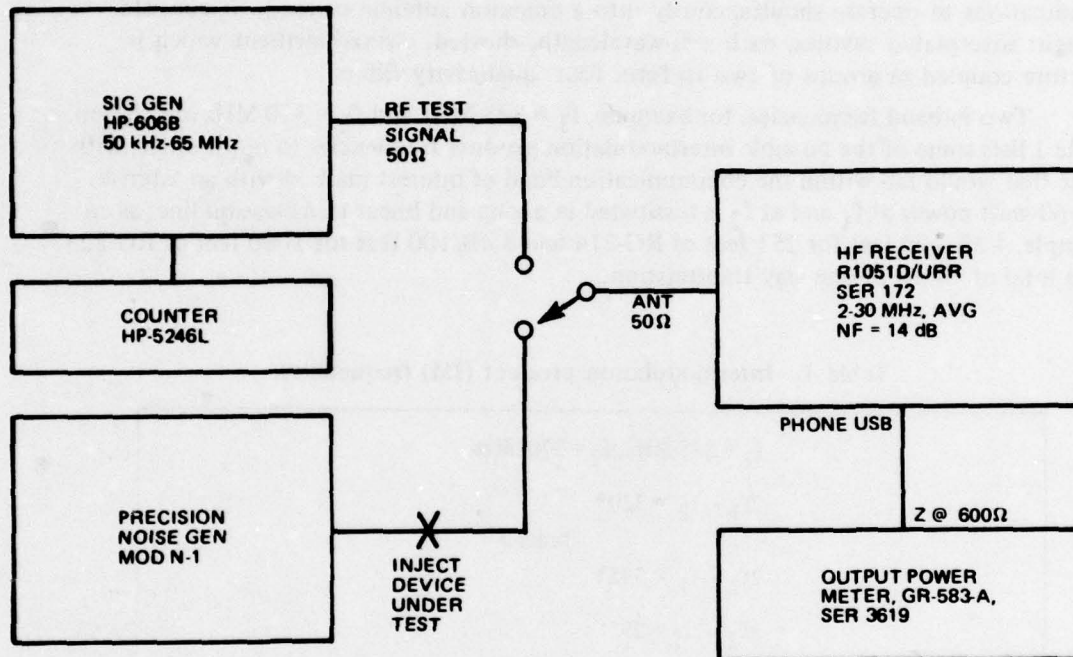
Figure 8. Block diagram of hf noise-figure measuring experiment.

Noise generation by uhf TPD's should be looked for by including them in the input of a SRC-20 receiver. This is to be fed with input signals at 225 and 400 MHz from a HP 608C signal generator modulated 90 percent at 1 kHz. At 6 μv input a GR 583-A output-power-meter is used to establish a (S+N)/N of ~23 dB at the receiver output. The presence of any of the uhf TPD's should have no effect at this level. With or without the devices, the minimum detectable signal should be in the order of 0.1 μv.

4.1.8 Radio Frequency Power Handling Capability

If a protective device is installed in a system it must be determined that firing or breakdown of the device will not occur while the system is operating in a normal manner. Normal radio frequency power, voltage, and current operating levels must be determined for a particular system.

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It is necessary to apply maximum operating power for one hour so that losses or changes in characteristics of the device because of possible heating effects can be determined.

Depending on the system under consideration, receive-only, transceive or transmit-only, the following should, where possible, be the subject of analysis or measurement:

(1) Receive-only: coupling from adjacent transmit systems with a TPD installed should be considered and induced voltage, and power levels of any extraneous signals determined.

(2) Transceive systems: any interfering signals produced because of the introduction of a TPD in the system must be analyzed. This is for single and/or multiple transceiver operations with and without multicouplers.

(3) Transmit systems: ability to accommodate multiple transmitter operation at high combined power levels with multicoupler.

4.1.9 Time Domain Reflectometry (TDR)

When making measurements aboard ship, it may be that environmental conditions and ship operational constraints will preclude many of the tests discussed above. For obvious reasons, there are ship commanders who will not want their communication systems subjected to any possibly destructive testing procedures. In this case, TDR testing on installed TPD's can give useful information about effects upon antenna-transmission line systems. This is a procedure already in use in a shipboard, electronic-installation, validation-test program; this is described and outlined in reference 11. The technique is, of course, equally applicable in laboratory testing with passive measurements on a TPD in a simulated system. One recommended instrument is Tektronix type 1502 reflectometer.

The Tektronix reflectometer, although designed primarily for measurements on cables and transmission lines, does give useful data on components and discrete elements. It functions by periodically generating a step-waveform with a period of 60 microseconds, an amplitude of 225 millivolts, a duration length of 10 microseconds, and a risetime of 110 picoseconds. The display, either cathode-ray-tube or a chart from a sampling readout, consists of the reflected signal superimposed on the incident signal. A reflection coefficient, ranging from zero to plus or minus one, is defined as $\rho = E_{reflected}/E_{incident}$ and is measured, in general, for a 50 ohm reference impedance, Z_{ref}. Thus, a cable or component impedance is defined as $Z = Z_{ref} (1 + \rho)/(1 - \rho)$ and an open-circuit or increased Z in a cable or a series inductor causes a rise or increase in the reflected signal display, that is, a positive ρ. A cable short, decreased Z, or a shunt capacitance gives a negative ρ. As a TPD most probably would introduce a discontinuity as either a very small shunt capacitance or series inductance, it is possible to measure these discontinuities from the magnitude of the small reflection (V_r) and knowledge of the rise-time (T_R) of the incident step function. As shown in Figure 9 and discussed in Appendix B, $V_s/2$ is the output voltage of the impedance-matched pulse source.

Two or more discontinuities or mismatches produce reflections that can be analyzed separately. However, there are complications in analyzing the oscilloscope display. The reflection from the first discontinuity is unaffected by the presence of others, but the succeeding discontinuities tend to become masked and distorted. As reflections are analyzed and their source eliminated from the TDR end of the cable, the complications introduced by reflections can be eliminated successively.
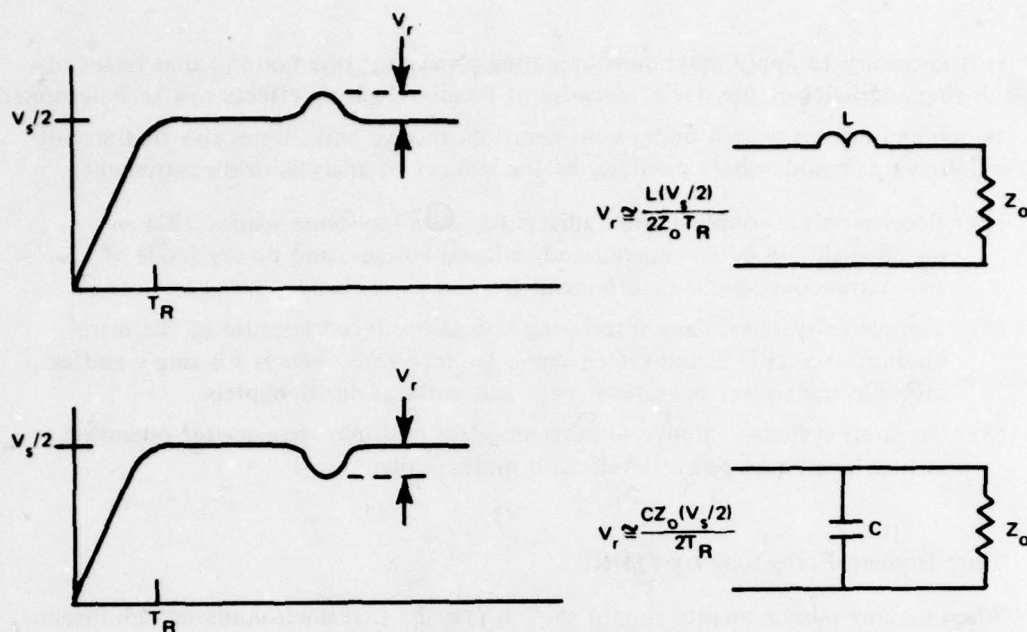
17

$$V_r \cong \frac{L(V_s/2)}{2Z_0 T_R}$$

$$V_r \cong \frac{CZ_0(V_s/2)}{2T_R}$$

Figure 9. Determination of small reactive reflection effects of a TPD by time-domain reflectometry. T_R is the pulse rise time, after Matick.

4.2 EMP TRANSIENT RESPONSE MEASUREMENTS

4.2.1 Instruments for Measurements

A wide bandwidth current and/or voltage sensor with output to a wide bandwidth oscilloscope with camera have been found to be the most useful instruments in the technique for analyzing non-repetitive waveforms that appear at various points in a system as a result of an incident EMP or simulated, that is injected, EMP. Single-sweep triggering by the transient makes possible an easily analyzed trace. An oscilloscope such as Tektronix Model 454A or the Hewlett-Packard 1722B allows observation of any portion of the waveform of combined EMP pulse and radio frequency power in terms of amplitude and time.

The following test procedures all involve the sampling of voltages and currents at various points in coaxial, transmission-line systems. Bird Electronic Corporation builds capacitive-coupled, voltage-measuring probes and T and M Research Products, Albuquerque, N.M., is a source for resistive-coupled probes that combine voltage and current sampling in a single device.

4.2.2 Transient Measurements

The following tests are required:

(1) Determine that the protective device either dissipates all the EMP-induced transient energy or enough of it to prevent equipment damage and/or system upset.

(2) Determine the length of time a protected circuit or system (full radio frequency power on) will be affected by a transient by means of high speed oscillography.

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(3) Determine that the protective device extinguishes while in a high power circuit.

(4) While a protective device is firing, some energy from a power transmitter will be dissipated in the protector. Determine the impact of this.

(5) Determine how a particular circuit or system might affect the protective device's operation.

(6) Consider and determine effects of multiple transients while conducting full power through the system.

These tests are to be made at hf using a NSWC-developed, damped, sinusoidal signal generator with a frequency of approximately 6 MHz. This simulates an EMP impinging on a high frequency, shipboard antenna. Charging voltage of up to 50 kilovolts on this generator results in a first period peak of approximately 30 kilovolts across a 50-ohm load. Tests of uhf devices can be at proportionally lower voltages and with a pulse source designed for that frequency range.

From the idealized cases of "monopole" antennae illustrated in Figures A2-A3 and A5-A6 in Appendix A, the following table for open circuit (OC) and 50 ohm loaded voltages is compiled. The 250 MHz values are simply extrapolated from the 2.5 and 25 MHz values on the assumption of peak voltages varying directly as wavelength, that is, antenna height. Topside reflectors and a possible Lloyd's mirror effect from sea-surface reflections could modify these predictions even to the extent of doubling them. A TPD could, depending upon its location, conceivably be subjected to the open circuit voltage.

Table 2. Estimated EMP-induced peak voltage on a "monopole."

Antenna Height (meters)	Frequency (MHz)	V_{OC} (kilovolt)	$V_{50\ ohm}$ (kilovolt)
30	2.5	900	170
3	25	95	17
0.3	250	9	1.7 ← V values inferred

The following terms and definitions are taken from reference 3. It is necessary to determine how these relate to parameters in specified systems and to device manufacturer's specifications.

(1) **Pulse Breakdown Voltage (V_{PB})**, peak voltage attained before the protector begins to conduct for a specific rate of rise of the applied transient. (Generally V_{PB} increases with increasing rates of rise of the applied pulse.) In the case of a 6 MHz damped sine wave we are considering, 1.2 kilovolts/ nanosecond—one-fourth of a period at 6 MHz. V_{PB} is also referred to as dynamic breakdown voltage, surge sparkover voltage, or surge striking voltage.

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(2) **Clamping Voltage (V_C)**, voltage across the protective device during surge conditions after any overshoot or spiking has decayed down.

(3) **Extinguishing Voltage (V_F)**, voltage at which the protector's self quench or self extinguish occurs.

The series of laboratory tests to be performed are, in order:*

(1) Set up NSWC pulser working into 50-ohm load without protective device and establish pulser characteristics for future comparison.

```
┌──────────────┐     ┌──────────────┐     ┌──────────────┐
│  NSWC HF     │─────│   V AND I    │─────│   50-OHM     │
│  PULSER      │     │   MONITOR    │     │   LOAD       │
└──────────────┘     └──────┬───────┘     └──────────────┘
                            │
                            ▼
                     ┌──────────────┐
                     │ OSCILLOSCOPE │
                     │  AND CAMERA  │
                     └──────────────┘

                      SINGLE SWEEP
                      INTERNAL SYNC.
```
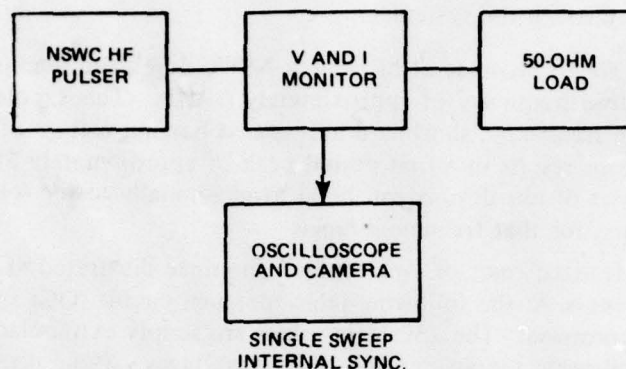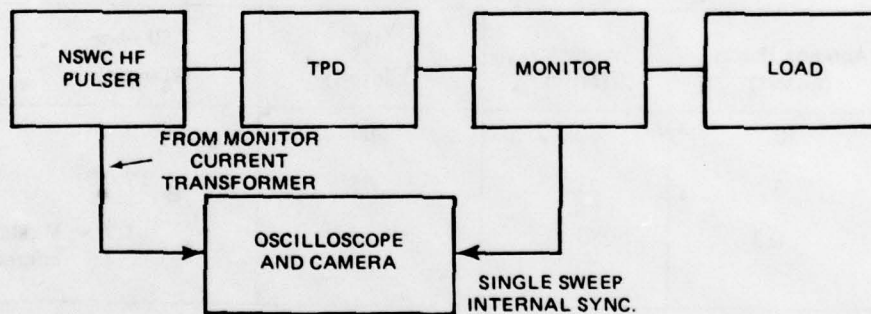
Determine frequency of damped sine wave output.
Determine current and voltage levels into 50-ohm resistive load.
Determine waveshape and duration of signal.

(2) Pulser working into 50-ohm load with protective device to determine characteristics of the protective device.

```
┌──────────────┐   ┌──────────────┐   ┌──────────────┐   ┌──────────────┐
│  NSWC HF     │───│     TPD      │───│   MONITOR    │───│    LOAD      │
│  PULSER      │   │              │   │              │   │              │
└──────┬───────┘   └──────────────┘   └──────┬───────┘   └──────────────┘
       │          FROM MONITOR               │
       │  ◄───      CURRENT                   │
       │          TRANSFORMER                 │
       │           ┌──────────────┐           │
       └──────────►│ OSCILLOSCOPE │◄──────────┘
                   │  AND CAMERA  │
                   └──────────────┘
                                   SINGLE SWEEP
                                   INTERNAL SYNC.
```
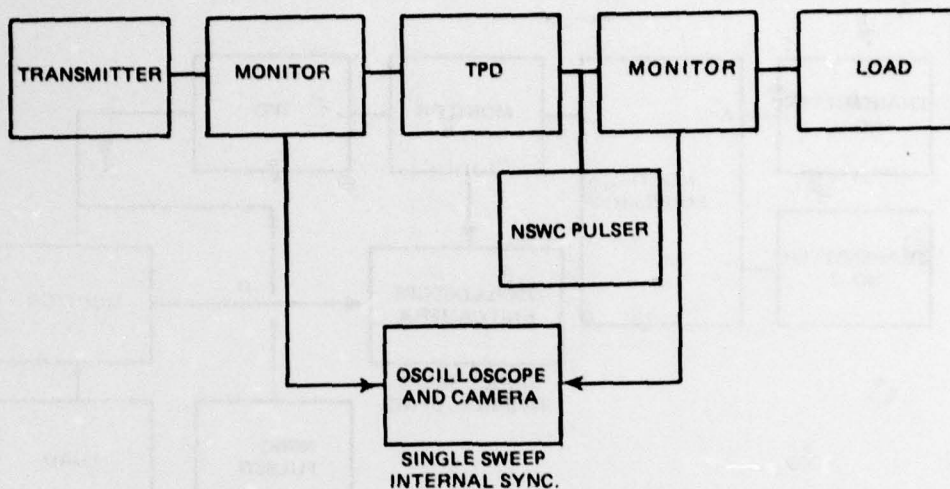
Determine V_{PB}.
Determine V_C.
Determine current through protective device and current to load.
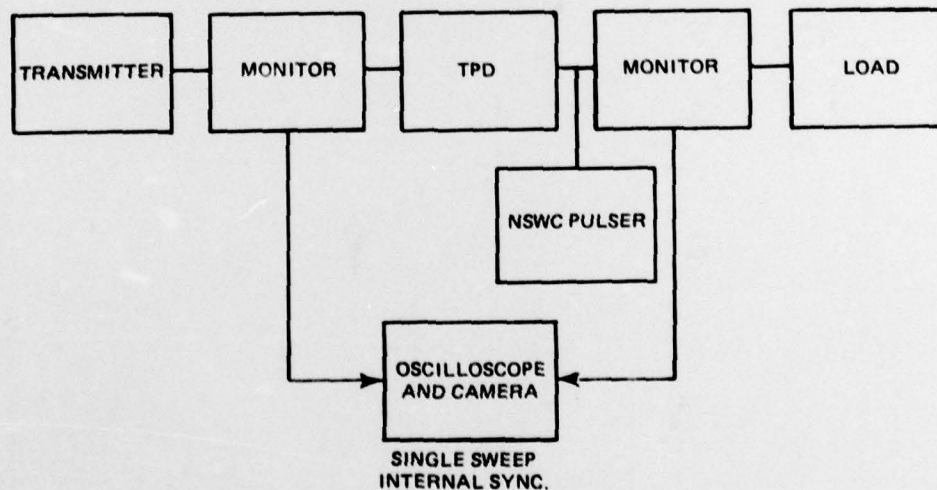Determine V_E extinguishing voltage and characteristics.

---

*As these systems are set up, it will be necessary to determine and specify such items as—types of equipment, length and types of connectors, operating levels and procedure.

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(3) Device installed in system. Direct injection of transient. No power applied to transmitting system.

```
+-------------+    +---------+    +-------+    +---------+    +--------+
| TRANSMITTER |----| MONITOR |----|  TPD  |----| MONITOR |----|  LOAD  |
+-------------+    +---------+    +-------+    +---------+    +--------+
                        |                          |
                        |              +---------------+
                        |              |  NSWC PULSER  |
                        |              +---------------+
                        |                   |
                        |    +---------------+
                        +----| OSCILLOSCOPE  |<----
                             | AND CAMERA    |
                             +---------------+
                              SINGLE SWEEP
                              INTERNAL SYNC.
```

Determine current into load and current back into transmitter.
Determine any effects of transmitter tuning or loading.
Decide if transmitter power should be applied.

(4) Device installed in system. Direct injection of transient. Power applied to system from transmitter.

```
+-------------+    +---------+    +-------+    +---------+    +--------+
| TRANSMITTER |----| MONITOR |----|  TPD  |----| MONITOR |----|  LOAD  |
+-------------+    +---------+    +-------+    +---------+    +--------+
                        |                          |
                        |              +---------------+
                        |              |  NSWC PULSER  |
                        |              +---------------+
                        |                   |
                        |    +---------------+
                        +----| OSCILLOSCOPE  |<----
                             | AND CAMERA    |
                             +---------------+
                              SINGLE SWEEP
                              INTERNAL SYNC.
```

Change frequency and power of transmitter and observe effects of transient on signal.
Determine any changes in firing of protective device.
Determine extinguishing characteristics and changes if any.
Determine repeatability of protective device characteristics.

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(5) Protective device installed in system with two transmitters. Direct injection of transient. Power applied to system from transmitters.
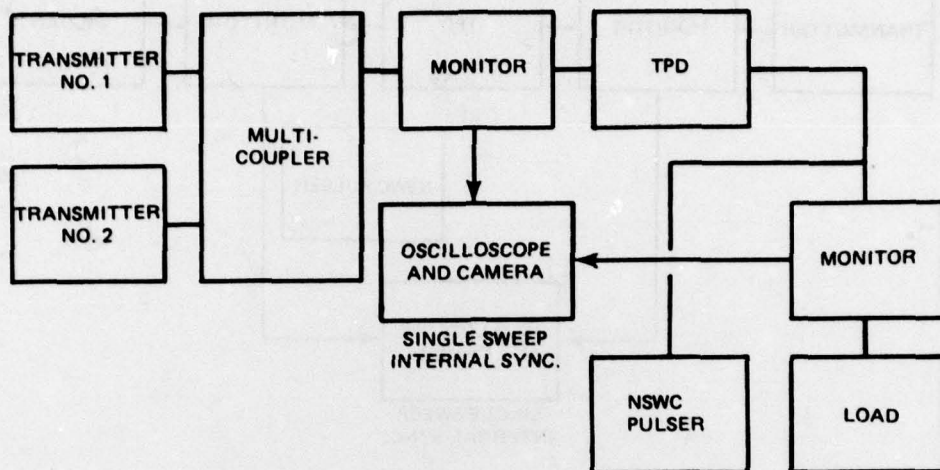
Determine/observe voltage and current as in previous measurements with the increased peak voltages and currents.

These are crucial measurements that more or less simulate operational conditions and will determine the suitability of a particular TPD.

5.0 REFERENCES

1. NOSC TN 437, Compatibility Test Procedures for Shipboard Transient-Protective-Devices (TPD's) at HF and UHF; by J. F. Theisen, L. S. Hansen, and R. W. Prather, 9 May 1978.

2. NOSC TN 496, Results and Procedures of Extinguishing Test of EMP Transient Protective Devices at HF; by R. W. Prather, J. F. Theisen, and L. S. Hansen, August 1978.

3. Defense Nuclear Agency, EMP (Electromagnetic Pulse) Preferred Test Procedures DNA 3286H; prepared by IIT Research Institute; Chicago, Illinois, February 1977.

4. NELC TR 1263, Shipboard Self-Interference; by W. M. Chase, W. E. Gustafson, and C.W. Tirrell, 22 January 1965.

5. NELC TR 1852, Analysis of Very-High-Order Frequency Components of Inter-modulation Interference Spectrum, by G. C. Salisbury, 26 October 1972.

6. NELC TD 206, Topside Intermodulation on USS MT WHITNEY (LCC 20), USS BLUE RIDGE (LLC 19) and USS IWO JIMA (LPH 2), by C. G. Salisbury, 27 December 1972.

7. NELC TD 336, Ship Radio-Frequency Survey Procedures for HF Frequencies, by W. M. Chase, 21 June 1974.

8. Defense Nuclear Agency, Electromagnetic-Pulse Handbook for Electric Power Systems DNA 3466F; by E. F. Vance, Stanford Research Institute, 4 February 1975.

9. NAVSHIPS 0967-177-3030, Shipboard Antenna Systems Volume 3, Antenna Couplers and Communications Antenna Systems, January 1973.

10. NAVSEA 0967-LP-266-1010, Hull Generated Intermodulation Interference Reduction Techniques for Forces Afloat, October 1971.

11. NAVSHIPS 0969-120-7010, Antenna and Transmission Line Reflectometer Measurement, January 1971.

12. Matick, R. E., *Transmission Lines for Digital and Communication Networks*, McGraw-Hill Book Company, 1969.

APPENDIX A

Figures A1–A8 illustrate the magnitude of possible environmental and technological problems that could be engendered by an electromagnetic pulse. Reproduced from reference 3, they show the predicted performances of 3 and 30 metre "monopoles" above a perfect groundplane and could, in general, be considered as the "worst case" condition where the incident E field is parallel to the antenna. As one would expect, the antenna, or for that matter, any metallic structure—mast, guy wire, etc., extracts considerable energy at its resonant frequency and a damped, high-voltage sinusoid appears at the terminals and a large current in conductors. There is also an almost "direct current" or single polarity component induced that decreases relatively slowly compared to the period of the oscillatory effects.

The titles of the figures adequately explain their content.
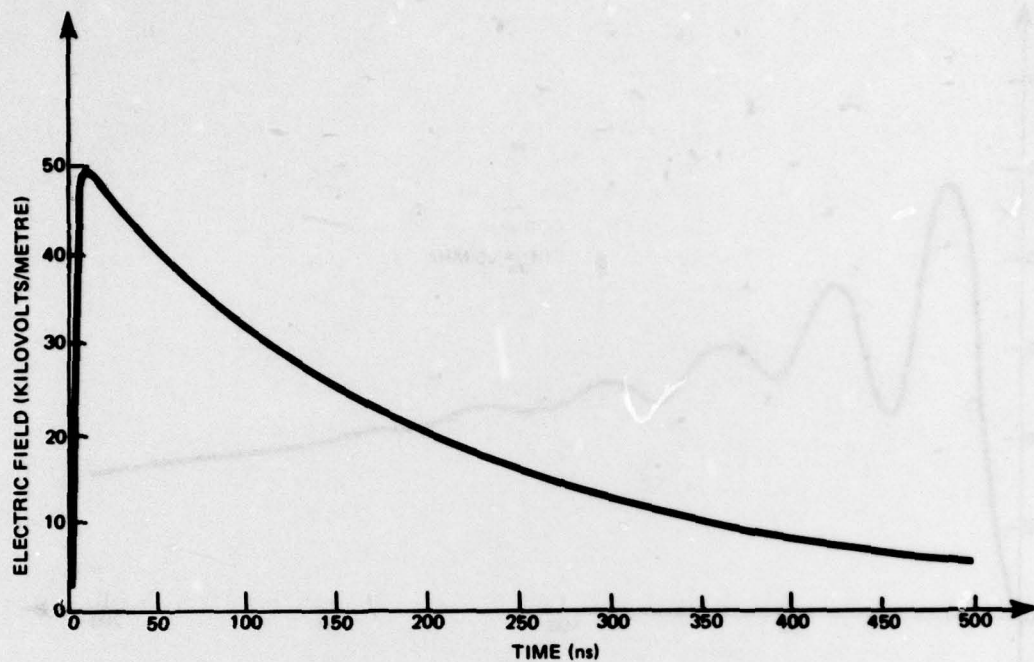
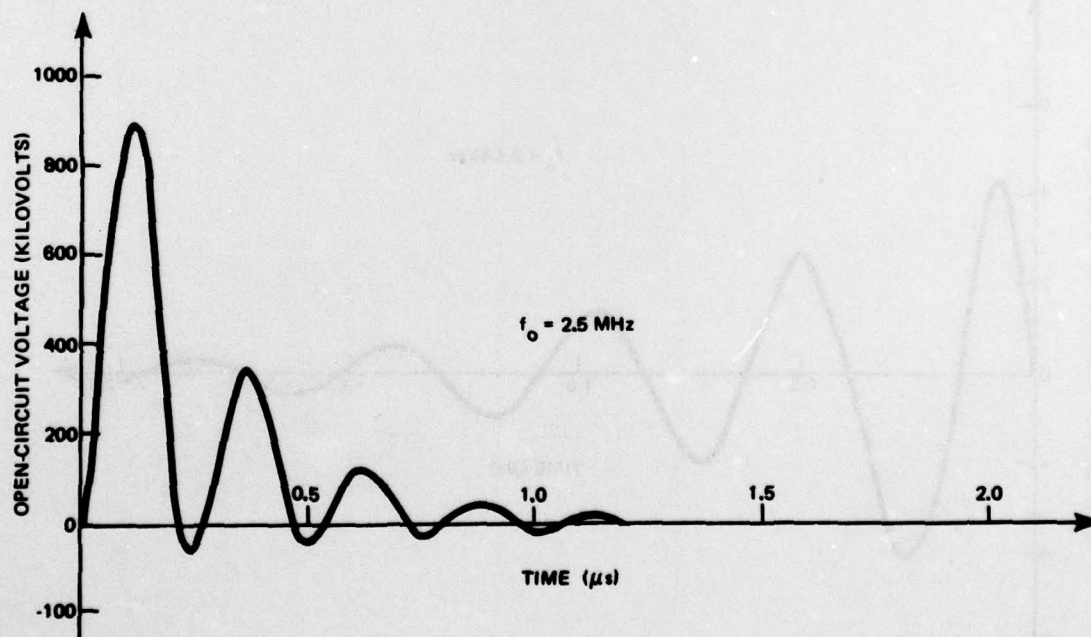Figure A1. Theoretical EMP waveform (possible worst case) from high-altitude, nuclear blast.

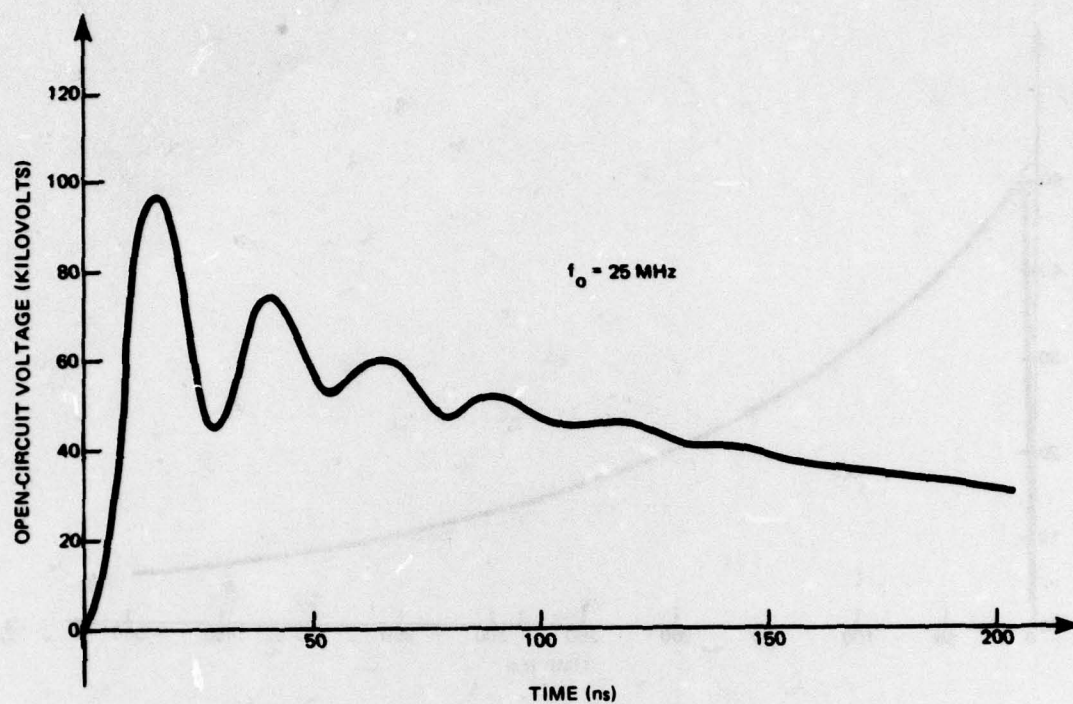Figure A2. Open-circuit voltage for a 30-metre monopole.

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Figure A3. Open-circuit voltage for a 3-metre monopole.
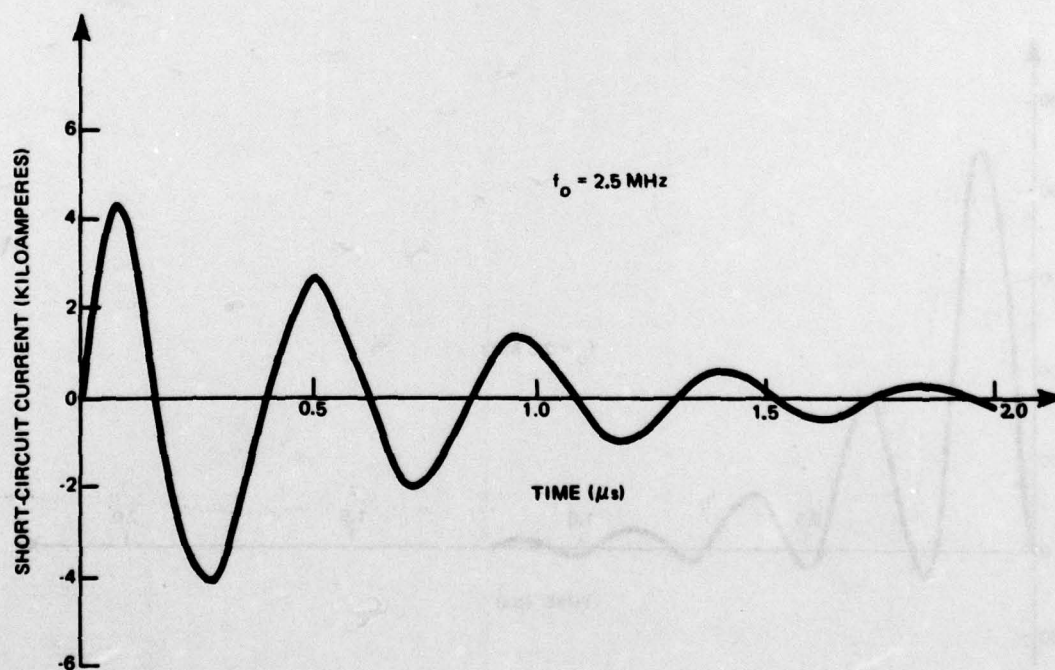

Figure A4. Short-circuit current for a 30-metre monopole.
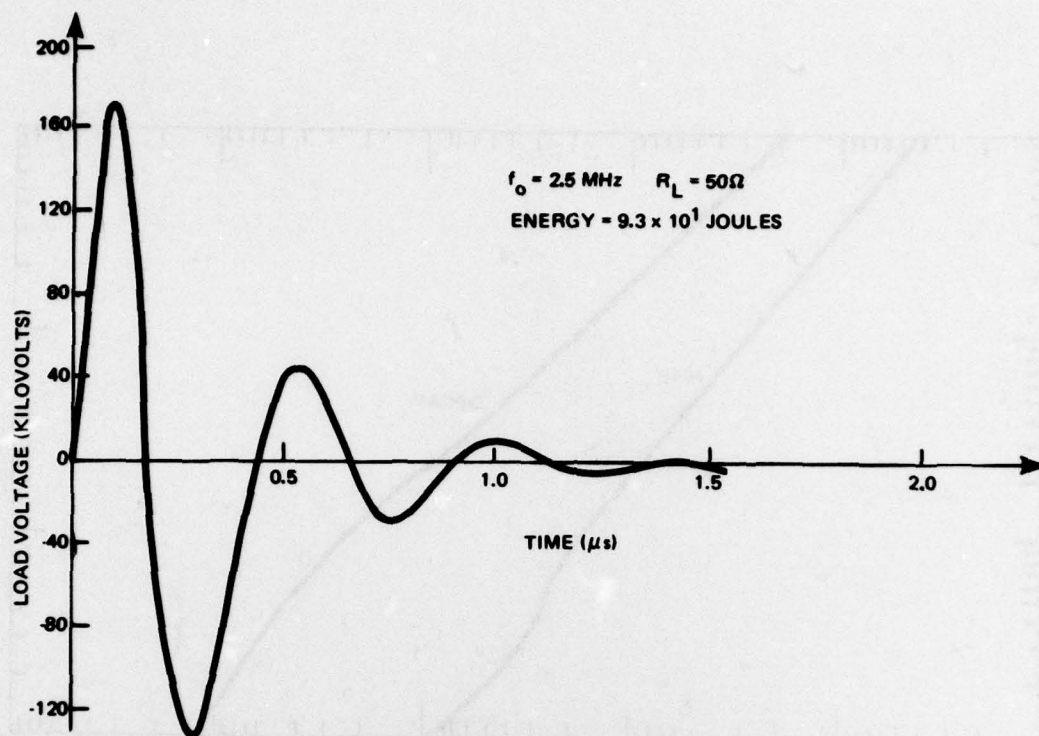
26

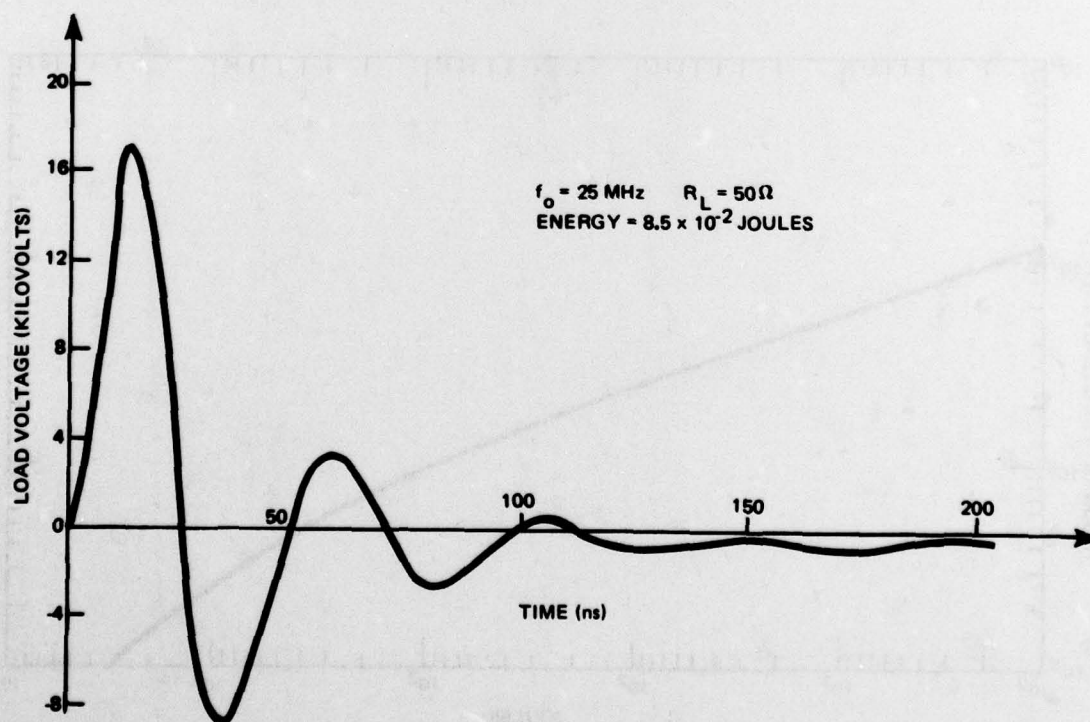Figure A5. Load voltage for a 30-metre monopole.
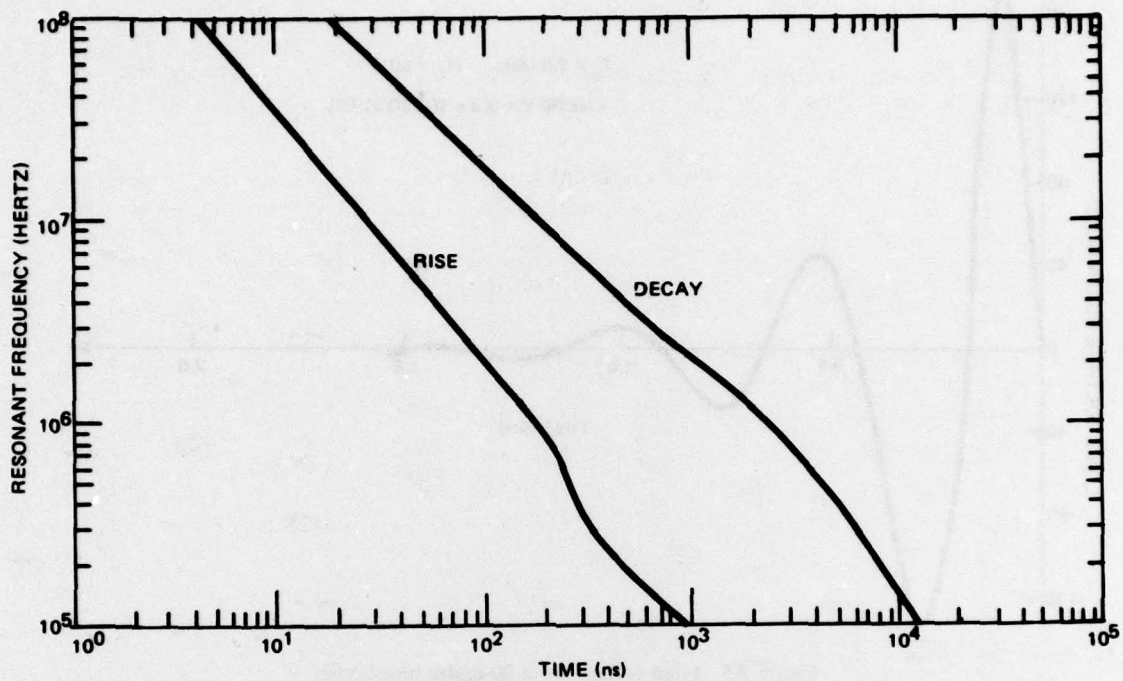

Figure A6. Load voltage for a 3-metre monopole.

27

Figure A7. Rise and decay of 50-ohms load voltage versus resonant frequency.
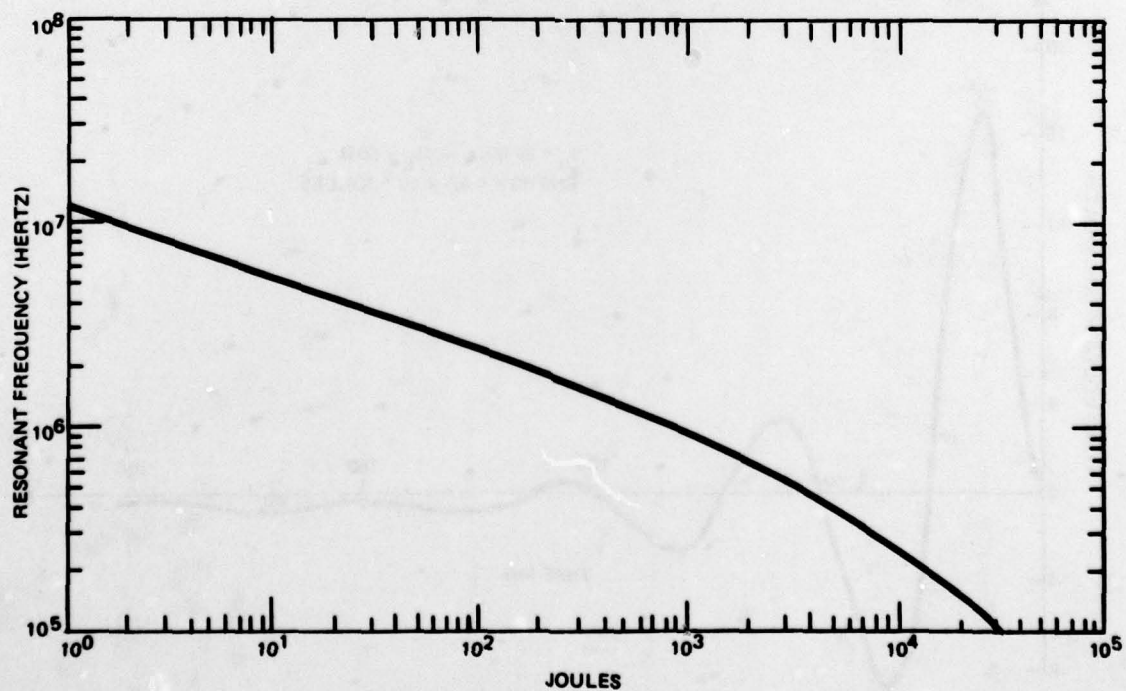

Figure A8. Energy dissipated in 50-ohm load versus resonant frequency.

APPENDIX B

Time-domain-reflectometry (TDR) is a technique uniquely suited to determination of TPD characteristics, especially when they either terminate or are included in a transmission-line system.

The following is a very brief development and summary of TPD application and is in large part from R. E. Matick, *Transmission Lines for Digital and Communication Networks*, McGraw-Hill, 1969 (reference 12).

The characteristic impedance of a transmission-line is given by

$$Z_O = [(R + i\omega L)/(G + i\omega C)]^{\frac{1}{2}} \cong (L/C)^{\frac{1}{2}} (1 - iR/2\omega L) \text{ ohm}$$

for reactive and resistive parameters per unit length and reduces to simply $(L/C)^{\frac{1}{2}}$ for the perfect case. Phase-shift is $\beta = \omega(LC)^{\frac{1}{2}}$ radian/metre and phase velocity is $v = \omega/\beta = (LC)^{-\frac{1}{2}}$ metre/sec for an angular frequency of ω radians/sec.

At a point X, the fundamental equations are $dV_x/dX = -(R + i\omega L) I_x$ and $dI_x/dX = -(G + i\omega C) V_x$ for voltage V and current I. Taking second derivatives in the usual wave equation manner, one defines a propagation constant, γ, given by $\gamma^2 = (R + i\omega L)(G + i\omega C)$ metre^{-2} and $\gamma = i\omega(LC)^{\frac{1}{2}}$ metre^{-1} for the lossless or perfect line.

From this, the voltage and current at a point X are given by simple but fundamental equations that include both traveling and standing waves, etc.

$$V_x = V_A e^{-\gamma x} + V_B e^{\gamma x}$$

$$I_x = I_A e^{-\gamma x} + I_B e^{\gamma x}$$

$$= Z_O^{-1} (V_A e^{-\gamma x} - V_B e^{\gamma x}) ;$$

all variables varying as $e^{i\omega t}$ and A refer to the input or generator end of the line and B to the load or sink end.

At the source, $X = 0$ and $V_A + V_B = V_S - I_S R_S$; V_S is the source potential (open circuit voltage), R_S the source resistance (nominally Z_O) for a current I_S. Then $V_A + V_B = V_S - (I_A + I_B) Z_O$, and as $I_A = V_A/Z_O$ and $I_B = -V_B/Z_O$ (see Matick) it follows that $V_A = V_S/2$ as one would expect in a matched-load condition. The other boundary condition V_B is determined at the load end where $X = \ell$ and $Z_\ell = V_\ell/I_\ell$, a bit more complicated as

$$Z_\ell = Z_O (V_A e^{-\gamma\ell} + V_B e^{\gamma\ell})/(V_A e^{-\gamma\ell} - V_B e^{\gamma\ell}),$$

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from which

$$V_B = V_A(Z_\ell - Z_o) e^{-\gamma\ell}/(Z_\ell + Z_o) e^{\gamma\ell} = (V_s/2) e^{-2\gamma\ell} (Z_\ell - Z_o)/(Z_\ell + Z_o).$$

V_A, I_A and V_B, I_B are opposite traveling waves and standing-wave ratio (SWR) is defined as $|V_A + V_B| / |V_A - V_B|$. This is renamed

$$\text{VSWR} = [1 + (V_B/V_A)] / [1 - (V_B/V_A)] = (1 + \rho_V)/(1 - \rho_V)$$

for a voltage reflection coefficient of ρ_V; the current coefficient is the negative of the voltage coefficient. Figure B1 is a general schematic of the system.

In TDR, the sinusoidal variation of $e^{i\omega t}$ is somewhat meaningless, although it would apply to all of the Fourier components of a pulse. Thus, the amplitude considerations apply equally well in both cases. In general, the pulse risetime determines the resolution and to resolve, say, 3 cm on a line one would need a 3.5 GHz bandwidth and a 100 picosecond risetime; as a rule-of-thumb $T_R \cong 0.35/\text{BW}$.

Figure B2 depicts various combinations of rather large reactive discontinuities that could possibly be encountered in some types of systems with protective devices. Except for shunt reactance in a loaded line, there is, in general, a doubling of the amplitude of the return signal and by measuring the time constant, it is possible to make a rough determination of the reactance.
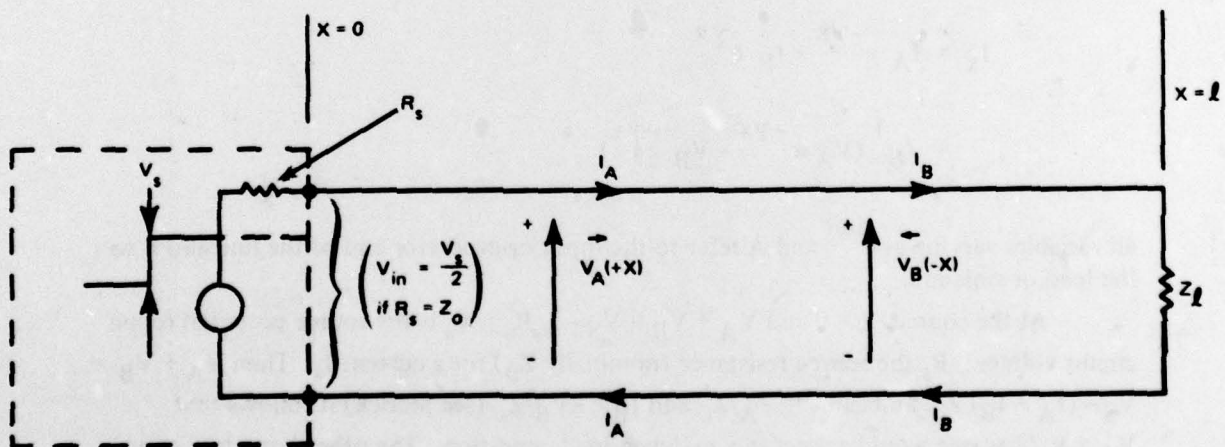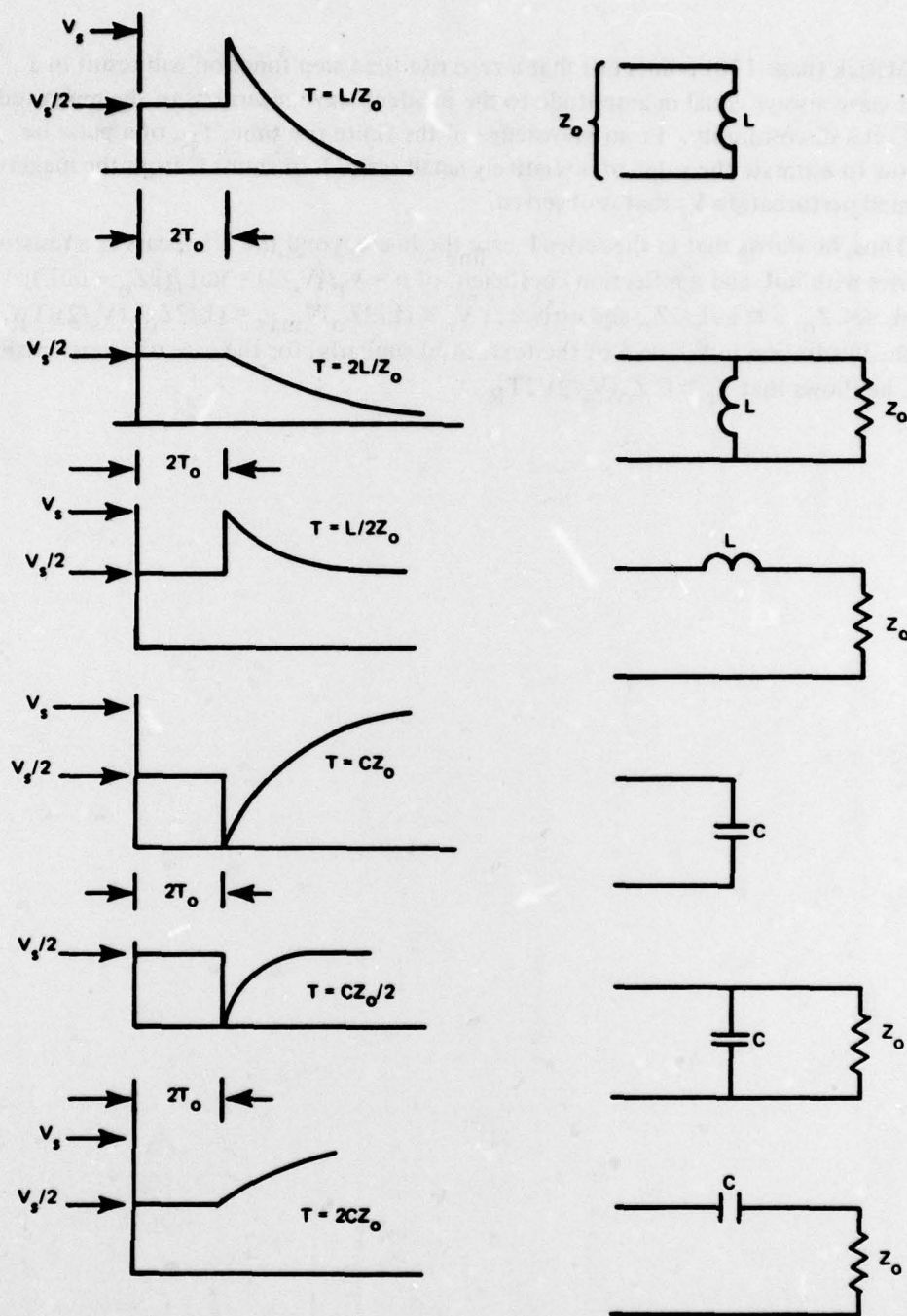

Figure B1. General schematic of terminated transmission line in step-function, time-domain reflectometry (TDR) after Matick.

T_O ≡ TRANSIT TIME, T ≡ EXPONENTIAL TIME CONSTANT

Figure B2. Reflections from combinations of relatively large reactive
discontinuities in TDR. Time constants much greater than
pulse rise time.

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$T_O \equiv$ TRANSIT TIME, $T \equiv$ EXPONENTIAL TIME CONSTANT

Figure B2. Reflections from combinations of relatively large reactive
discontinuities in TDR. Time constants much greater than
pulse rise time.

Matick (page 170) points out that a zero rise time step function will result in a reflected wave always equal in amplitude to the incident wave regardless of the magnitude of L or C at a discontinuity. From knowledge of the finite rise time, T_R, of a pulse he shows how to estimate the value of a relatively small series L or shunt C from the magnitude of the small perturbation V_r that is observed.

Thus, he shows that in the series L case the line beyond the L appears as a resistor Z_o in series with $i\omega L$ and a reflection coefficient of $\rho = V_r/(V_s/2) = i\omega L/(2Z_o + i\omega L)$; and if $\omega L \ll Z_o$, $\rho \cong i\omega L/2Z_o$ and arrives at $V_r \cong (L/2Z_o)V_{max} = (L/2Z_o)(V_s/2)/T_R$, to give the illustration in Figure 6 of the text. And similarly, for the case of a very small shunt C, he shows that $V_r \cong C Z_o(V_s/2)/2T_R$.

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